Volume manipulation using cut and paste operations and its applications

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1 Introduction

One of the problems associated with population aging is the increased occurrence of knee and hip joint diseases. As a result, the need for both total knee arthroplasty (TKA) and total hip arthroplasty (THA) is also increasing. TKA and THA are surgical techniques used for replacing knee and hip joints with artificial components (an assortment of implants), respectively. Two-dimensional computed radiography (2DCR) images of the limb are conventionally used in preoperative planning. Despite being inferior to other imaging modalities, 2DCR is used because these X-ray images acquired in standing position contain the information required for preoperative planning. Therefore, depending on the techniques and the experience of the surgeon, large differences arise in procedures such as positioning the implants and determining the cutting plane and the volume of the bone. To solve these problems and alleviate some of the burden on surgeons during preoperative planning of TKA and THA, we have developed a 3D surgical planning system that can be used on a personal computer. The system allows the user to manipulate 3D templates of TKA and THA components as well as to cut and paste bone fragments precisely in three-dimensional (3D) computed tomography (CT) images. In this paper, we describe the details of interactive cutting and pasting functions for 3D images and apply these functions in our 3D-based surgical planning system. We also evaluate the proposed manipulation techniques by using several CT images of actual patients.

2 Multi-volume operations for 3D images

Simultaneous processing of images created by the different modalities of CT and magnetic resonance imaging (MRI) is widely used in clinical medicine. Although CT can be used for the visualization of bones such as the femur (thighbone) and the tibia, it is not as effective for the visualization of cartilage (soft tissue) in knee joints. Since MRI can be used for the visualization of cartilage, both CT and MR images are utilized for preoperative planning. Conventional 3D image processing is used for manipulating individual 3D images. However, the advent of 64-bit operating systems, the constant improvement in CPU (central processor unit) and GPU (graphics processor unit) capabilities, and the increase in memory capacity of PCs have made it possible to manipulate multiple 3D images simultaneously on an ordinary personal computer.

2.1 Cut operations using stroke

Although three side displays are commonly used for manipulation of 3D objects in computer aided design (CAD), the manipulation is a difficult and time-consuming task. Therefore, we propose a tablet-based method for visualizing 3D objects. We utilize a directed line, (referred to as a stroke) and define the cutting plane in 3D space on the display. The image is partitioned by the plane defined by the directed line. The direction of the line (either positive or negative) represents the normal direction of the cutting plane. Here, we show several examples of the proposed method in operation. The front and back surfaces of the cutting plane are defined by the direction of the arrow (in order of ①→②), as shown in Figs. 1 and 2.
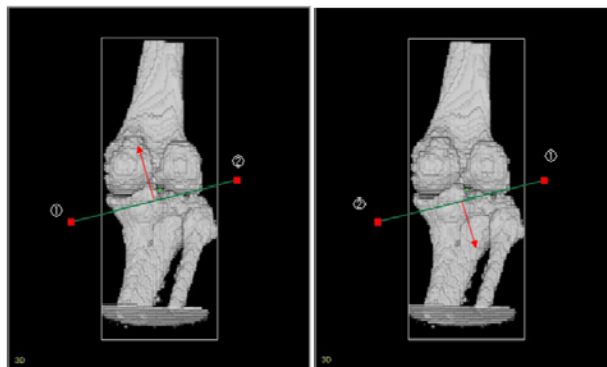

Fig. 1 Placement (case A)   Fig. 2 Placement (case B)

If there is only a single cutting plane, the result shown in Fig. 3 will be the same regardless of the orientation of the front and back surface of the cutting plane. However, if the number of cut planes is two or more, the results will change depending on the combination of front and back surface of each cutting plane. Also, the cut plane is regarded as an extension on the display (dotted line in Figure 4), and processing is performed by using the two cutting planes to divide the space into two regions, namely the region enclosed by the front surfaces of the planes, and the region corresponding to the remaining space. If there are two cutting planes, the direction of each segment in the stroke can be used to specify the area to be cut.
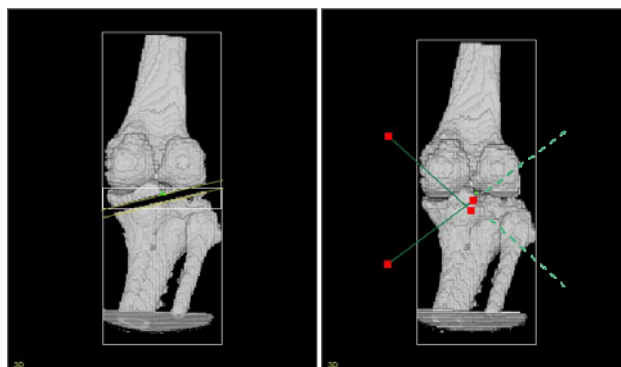

Fig. 3 Results (1)   Fig. 4 Extended lines

When two cutting planes are placed in the 3D image, the result is different depending on the direction of the normal to the surface of the cutting plane. The two cases are shown below in Figs. 5 and 6.
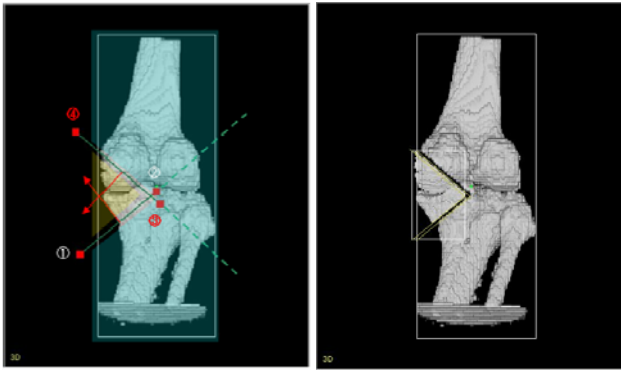

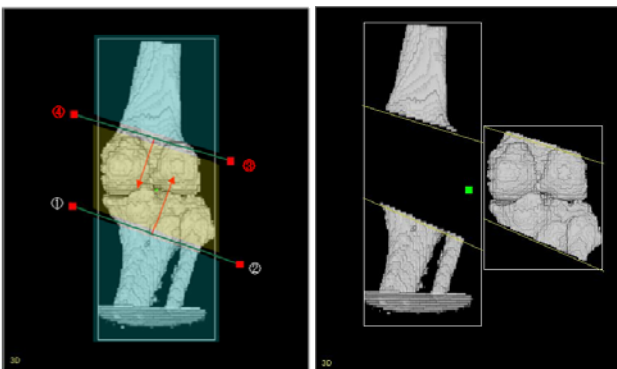Fig. 5 Two cutting planes and the resulting cut region (case C)

Fig. 6 Two cutting planes and the resulting cut region (case D)

2.2 Paste operation

The paste operation allows for matching two planes. For example, the surfaces of two cutting planes in the volume image are pasted together. This feature is used when two images need to be connected to each other with high precision. In our system, the user selects two surfaces interactively, and the first surface is re-located onto the second one. After the placement, the volume image with the first surface can be moved and rotated horizontally onto the other surface (Fig. 7).
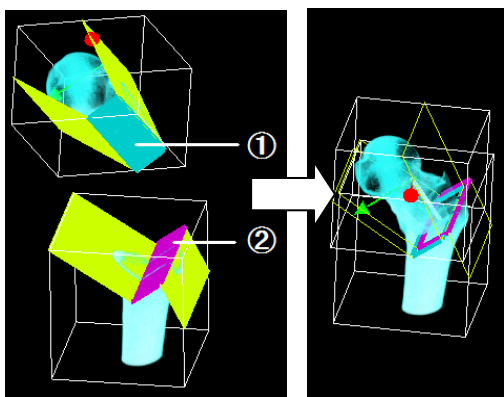

Fig. 7 Paste operation and its result

2.3 Drawing auxiliary lines and measurement functions

In general, it is difficult to set the correct surfaces of cutting planes in 3D space. In order to facilitate this operation, we have implemented a function allowing the user to draw auxiliary lines before placing the cutting planes. We have also implemented measurement functions for angles and lengths for both cutting planes and auxiliary lines.

3 3D surgical planning system with cut and paste operations

3.1 System overview

Our 3D surgical planning system allows the user to manipulate multi-volume data, and we have developed cut and paste operations to improve the accuracy of surgical procedures. In addition, the system supports several other useful functions to help with preoperative planning, such as DICOM image loading, volume rendering, image segmentation, implant placement (3D templating), and drawing auxiliary lines.

Our goal is to reduce the time required for the preoperative planning procedures to around 30–40 minutes. Therefore, our system, unlike traditional CAD and CG systems, has been designed and implemented to allow for cutting, moving, and rotating objects intuitively by using a mouse. The mouse is suitable for performing such rotation and movement operations on the screen. Each subset of several images is selected with the mouse, and the selected images can be moved and rotated interactively. Figure 10 shows the simulation results for posterior rotational osteotomy, which is a common clinical procedure.

Our 3D surgical system is written in VC++ using OpenGL on the Windows family of operating systems, and our volume renderer utilizes the 3D texture function of OpenGL[2]. Grayscale images are converted to color images, stored in 3D texture memory and rendered by the GPU.

3.2 Transtrochanteric Rotational Osteotomy for Osteonecrosis of the Femoral Head

Osteonecrosis of the femoral head is often caused by treatment with glucocorticoid for collagen disease or chronic alcohol abuse. When the patient is young, transtrochanteric rotational osteotomy of the femoral head should be considered in order to preserve the hip joint. In this surgical procedure, several cutting planes are placed and the femoral head is rotated in order to shifts weight from necrotic lesion to the intact bone. (Fig. 10). Line A in Fig. 10 shows the axis of the femoral neck in anterior-posterior view, and line B shows the axis of the femoral shaft in a lateral view. Line C shows the axis of the femoral neck with the physiological anteversion. The basic cutting planes of the femur are defined as planes (1), (2), and (3). Figures 11 and 12 show the shape of the proximal femur before and after the anterior rotation of the femoral head.
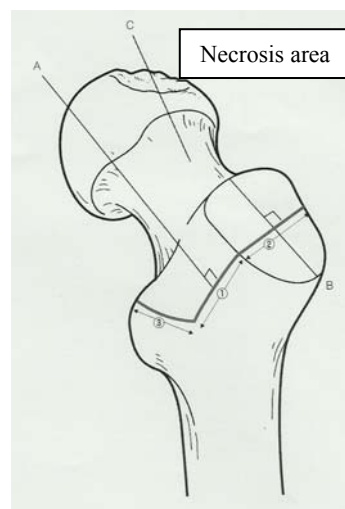

Necrosis area

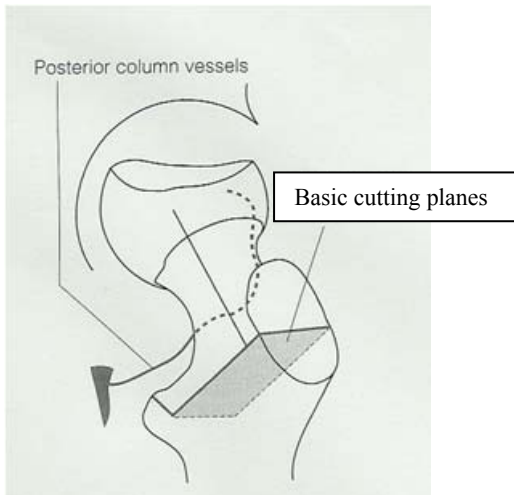Fig. 10 Femoral head anterior rotational osteotomy (ARO)

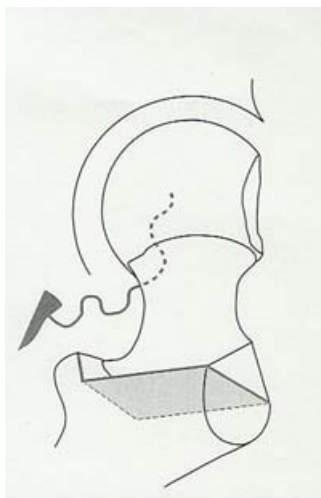Fig. 11 Femoral head ARO before correction

Fig. 12 Femoral head ARO after correction

In order to segment the bone region from the CT image, we utilize the histogram-based segmentation method implemented in Volume Extractor Ver.3.0, which was developed at Iwate Prefectural University. By interactively specifying the CT value of the cortical bone, we extract the bone region and separate the region into pelvis and femur (Fig. 13). The necrotized area is shown in red in Fig. 13. Figures 14–16 show the process flow of the cut and paste operations for femoral head ARO surgery in our 3D surgical planning system.

Fig. 13 Segmentation of femoral head bone. Regions shown in red correspond to the necrotized area.
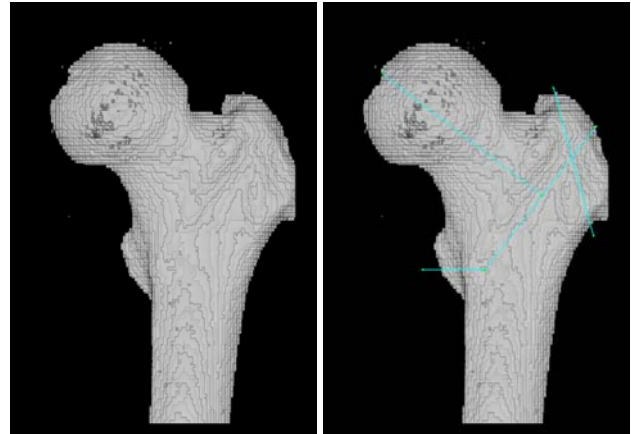
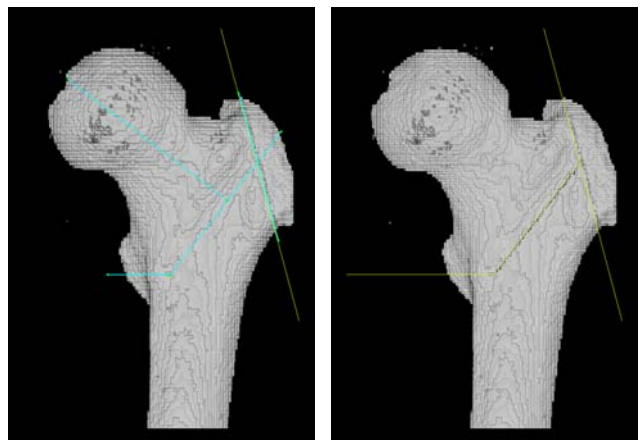Fig. 14 Drawing auxiliary lines (shown in blue)

Fig. 15 Placing cutting planes on the femur. Auxiliary lines are shown in blue and cutting planes in yellow.
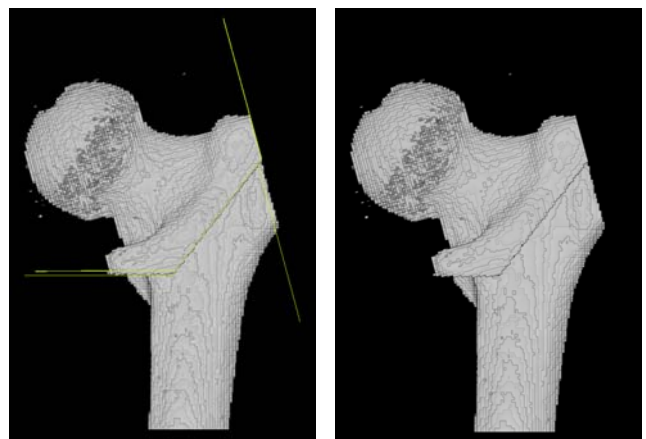

Fig. 16 Rotation of the femoral head and the final result

3.3 High Tibial Osteotomy

High tibial osteotomy is a joint-preserving surgical procedure for medial compartmental osteoarthritis of the varus knee, and ideal candidates are young and active patients who are not suitable for total knee arthroplasty. In this procedure, alignment of the leg is corrected by resection of the wedge at proximal tibia denoted as AOA in Fig. 17, and the body weight is supposed to be transferred to the preserved normal lateral side of the knee. During surgery, several K-wires are inserted into the tibia by using surgical instruments with angle adjustment feature

in order to obtain ideal correction angle. The optimal femorotibial angle (FTA) after HTO is reported to be in the vicinity of 166–168°. Figures 18 and 19 show the processing flow of the cut and paste operations for HTO in our 3D surgical planning system.
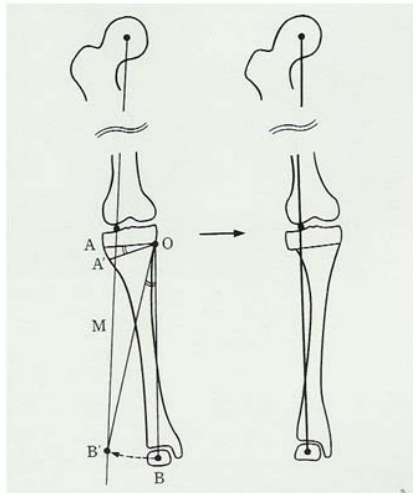

Fig. 17 High tibial osteotomy

4   Conclusion

In this paper, we described the details of interactive cutting and pasting functions for 3D images, and we have implemented these functions into our 3D surgical planning system. Precise and efficient surgery planning increases the quality of life of patients and reduces burden on the surgeons during all aspects of artificial joint surgery. Our system allows users to manipulate 3D images directly, and the newly implemented cut and paste operations are extremely powerful tools for surgeons.

Surgeons have evaluated the ease of use of these manipulation techniques by using several CT images of patients scheduled for TKA and THA. They have also used them to perform several complicated osteotomies such as posterior rotational osteotomy for non-traumatic osteonecrosis of the femoral head.

References

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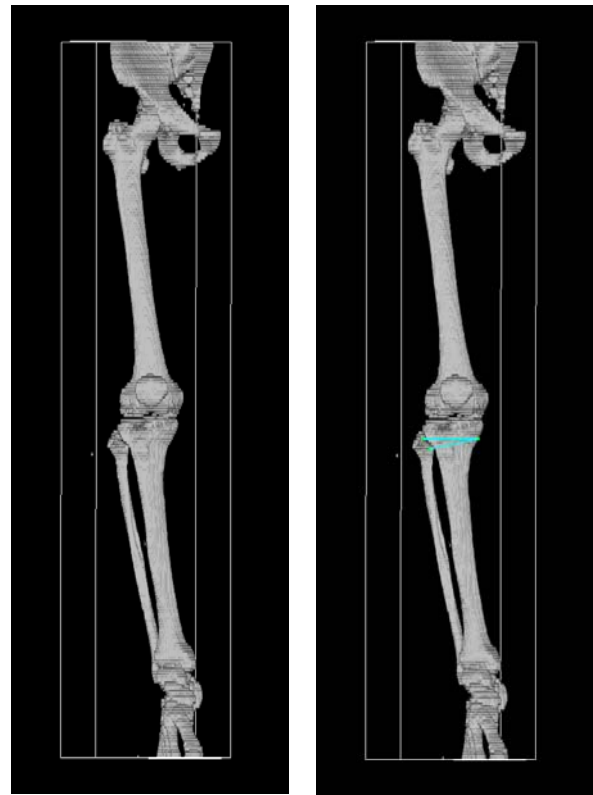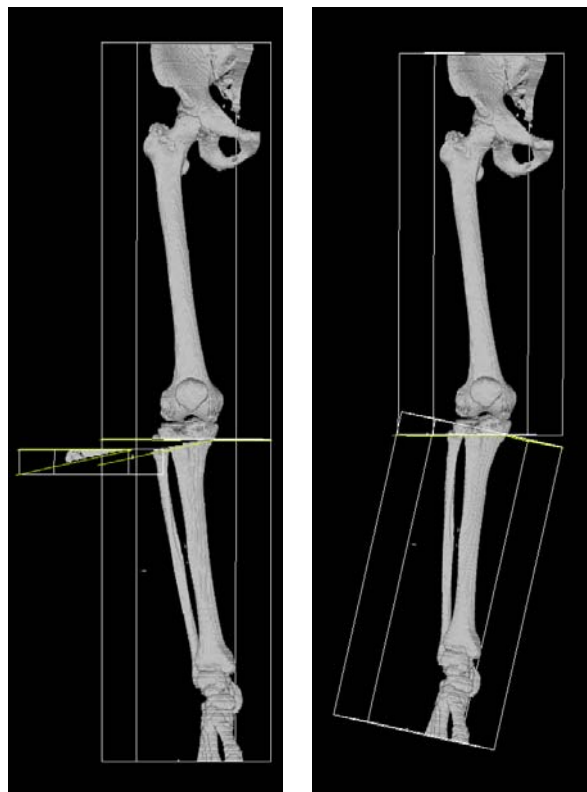
Fig . 18 Results of drawing auxiliary lines

Fig. 19 Results of cut and paste operations